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INTERACTIVE PHYSICS SIMULATIONS APPEAL TO FIRST-YEAR STUDENTS

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Figure 1. Main menu screen offers students these four choices: Preconceptions (Preconceptos), Simulation (Simulación), Tutorial, and Evaluation (Evaluación).

At present, a great deal of effort is being devoted to improving the quality of educational software for physics[1-10] and expanding the use of computers in physics teaching.[11] Over the last five years, our research team has developed several programs based on simulations of physical phenomena.[12,13] In addition, we have also put them into practice, complementing the traditional instruction of first-year students. The students who used these programs got better grades than those who did not use the simulation programs, regardless of whether they were in the same class or in previous classes.[14]

Based on this experience, and after a fruitless search for software that met our particular needs, we decided to develop a whole new suite of programs of our own: the Interactive Simulation (INSIMU) Project. The programs make use of the widely available Microsoft Windows environment and are based on up-to-date educational practices. Each program includes a simulation laboratory and a tutorial for the specific class of physical processes under study. As part of the IN-SIMU Project, we intend to compare students' understanding and misconceptions before and after they use the software.

In the next section we outline the general characteristics of the INSIMU Project and the essential features of the programs. Later in the article we provide a more detailed

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description of a specific program devoted to the study of elastic structures.

Main features of INSIMU programs

The programs have been designed for university students studying engineering and science. The purpose of the project is to provide students with a deeper understanding of some topics in their syllabi and to introduce them to numerical methods, simulation, and computational physics. The programs do not cover all the topics of a subject—just a few in which the use of simulation is really needed. Appropriate topics would include the theory of elasticity, nonlinear oscillations, three-body problems, electrostatic problems, and heat conduction. At present, the project includes topics on classical mechanics (central forces, particle interactions, and linear and nonlinear oscillations), electricity and magnetism (electrostatic fields and potentials), modern physics (atomic models, quantum mechanics of the hydrogen atom), heat transfer (temperature distribution in solids), and mechanics of continuous media (elasticity).

We have attempted to provide the software with both integrative and interactive characteristics:

- Integrative characteristics. Each didactic unit has a similar configuration and consists of four parts: Previous Knowledge, Tutorial, Simulation, and Evaluation. Each of the units is an integrated whole: it unifies all the components of the educational process in one application. As part of
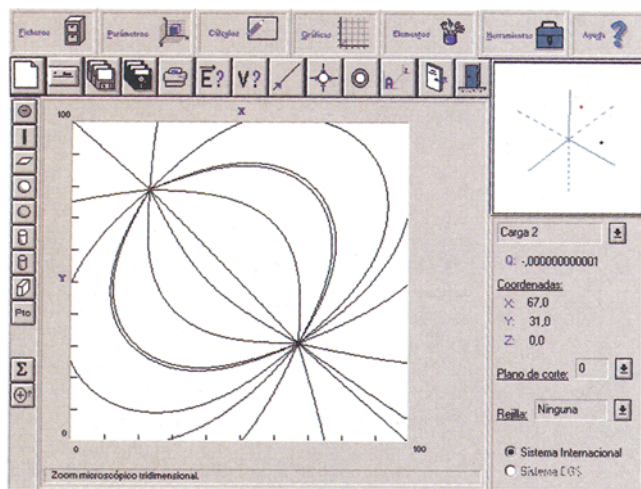
Figure 2. Click-and-drag procedure lets students set up this simulation of an electric dipole field.

the evaluation process, students' understanding is tested both prior and subsequent to the use of this software.

- Interactive characteristics. These programs permit users to design or modify the physical system being simulated, by choosing the variables, elements, and physical conditions. Tutorials can be accessed from any point in the programs via hypertext links.

The user interfaces for these programs are user-friendly for their intended audience of first-year university students. The environment is the familiar Windows standard. To make any of the selections, users can activate interchangeably the mouse, hot keys, or bar menus, and a help menu is always available. Animated icons illustrate the functions of different buttons. The Windows calculator and Word (for word-processing) are accessible from the programs.

The aim of the Previous Knowledge section is to test students' knowledge prior to working with the application, whereas the Evaluation session assesses their understanding after using the Tutorial and Simulation sections. These two steps provide information on the effectiveness of the INSIMU programs.

Selection of the Previous Knowledge or the Evaluation sections from the main menu (see Fig. 1) activates a test consisting of questions that can be determined by the teacher (see below). The multiple-choice questions appear one by one and are loaded randomly from a database file. The programs grade the answers and report a test mark to the student.

Teachers can modify, add to, or substitute for the database files, thereby adjusting the test questions to their specific needs. These files are password-protected so that only the teacher is able to access them.

The Tutorial section, in hypertext, explains the fundamental concepts, methods, and physical laws involved in the process under study. It includes animated graphics when needed. Its format is that of a Windows help file, with keywords, index, and cross-references.

In the Simulation section, the user learns about a specific physical system. The properties of the system are described, and, when appropriate, its time evolution can be simulated. In some cases, the system can be built by the user, who also fixes its initial conditions and the value of the parameters. For example, in the study of electrostatics, the user can select from a menu of electrical elements such as point charges, lines, planes, and spheres by clicking a mouse (see Fig. 2). The elements can be dragged to the position in which the student wishes to place them.[15] Similarly, in the study of linear and nonlinear oscillations, variables are selected by mouse click and dragged to the coordinate axes (see Fig. 3). In this way users display the motion graph for the initial conditions that they have chosen.

Users do not have to do programming. All they need to do is to select a simulation experiment, specify the quantities they wish to observe, and give appropriate values to the relevant variables. Nevertheless, the student can find out how the program works and how the simulation is done. This information is available in a Word file that explains the main numerical methods used and relates them to the physical aspects of the problem considered. In another Word file, exercises and suggestions for simulation are offered as guidance to the students.

We have avoided simplifications that could mislead the students. For instance, the software models electrostatic systems formed by charged dielectrics in three-dimensional space with the real symmetry. We make use of fast algorithms, so that we can provide exact solutions whenever possible. As a result, the computer is able to display a realistic simulation of a numerical experiment, as specified by the
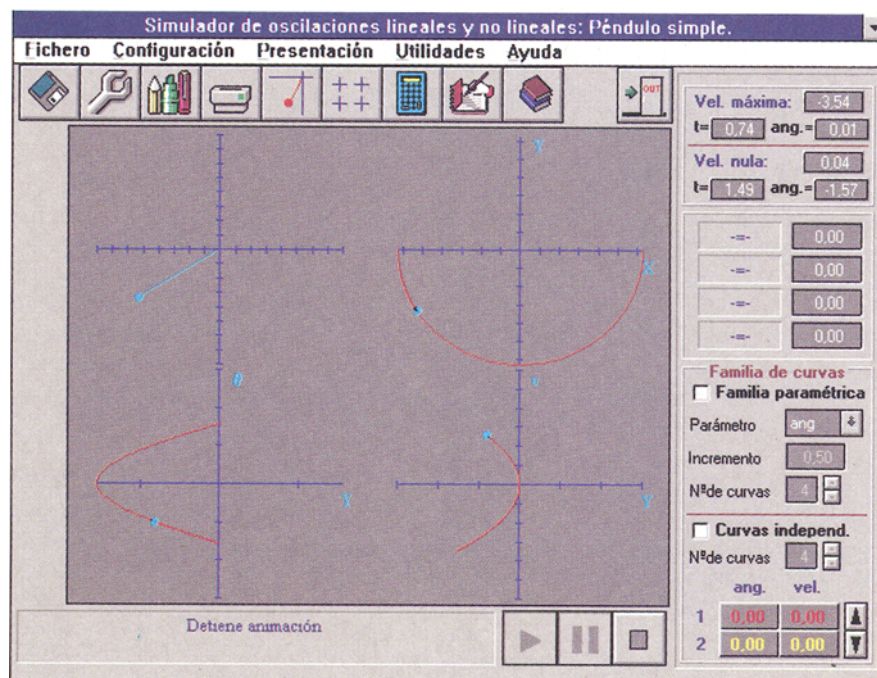

Figure 3. Students can readily set up an animated simulation. Here the user has specified display of the motion curves for a simple pendulum (péndulo simple).
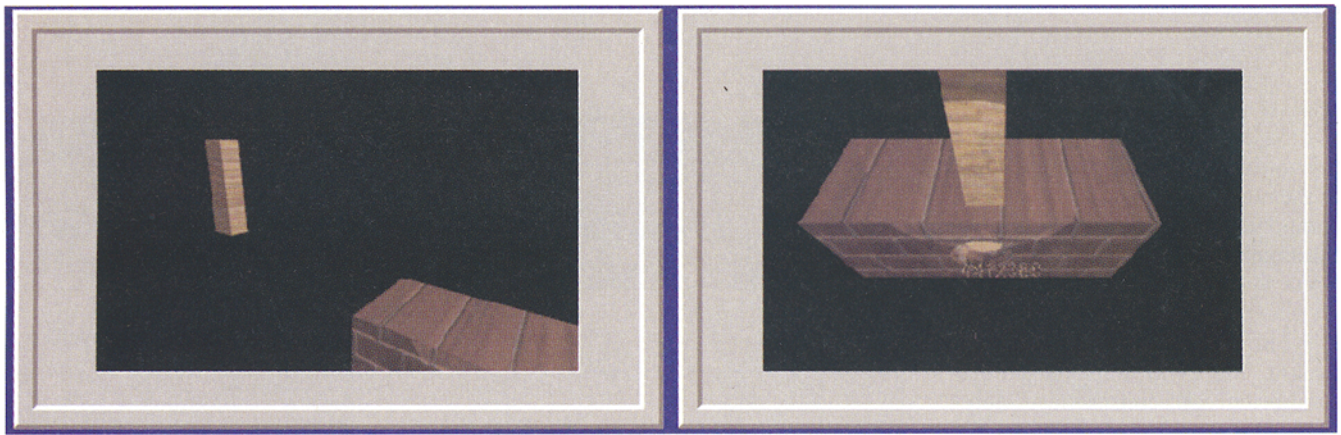
Figure 4. Concrete block falls to the earth and induces an internal reaction in these scenes from a mechanics illustration designed to capture students' attention.

user, with a time delay that lies within the attention span of typical first-year students.

Each program is accompanied by a booklet containing hard-copy versions of the Tutorial, instructions on how to use the software, and simulation exercises. The minimum hardware requirement for INSIMU programs is a computer with at least a 386 processor, 4 Mbytes of RAM, a VGA display, and Microsoft Windows 3.x or Windows 95.

The INSIMU Project includes a complementary software package named GestorWin.[16] This is, essentially, a database manager designed to monitor students' academic development. It can keep track of both conventional and INSIMU evaluations. GestorWin also permits statistical analyses of grades according to criteria such as age, sex, and previous schools.

Theory-of-elasticity simulation

Like all the INSIMU programs, the elasticity-theory software was developed using Windows with Visual Basic Pro version 3.0.[17] The application environment is supported by a series of screens designed using the Visual Basic programming system. Visual Basic uses programming oriented to events. Each object has different properties and methods that may be modified both in design time and in run time. The events are linked with objects via code. Sequential program structure is thereby avoided. All application screens share a common design regarding color, structure, fonts, and buttons.

The INSIMU theory-of-elasticity unit contains six different simulations. Due to the complexity of the study of tensions and inner reactions within the elastic field, we have opted for simulating only the most representative examples, which correspond to classic problems in elasticity.[18-21] The student determines the initial conditions—physical variables, types of material to be used—and chooses the points or planes where he or she wishes to calculate the tensions and inner reactions. Numerical and graphic results can be obtained for the following situations:

- Semi-infinite body subjected to a load applied to a point on the boundary plane.
- Semi-infinite sheet subjected to a load at a point on one edge.
- Straight piece subjected to pure flexion in a plane of symmetry.
- Rectangular piece in a projection with a load on the free end.
- Thin plate subjected to stresses.
- Bent bars.

Each of these simulations has its own job screen in which users must enter the data necessary to carry out the simulation and obtain the corresponding results.

All these screens are of similar design, and the Interactive Simulation Laboratory will therefore be described for the first example only: a semi-infinite body subjected to a load applied to a point on the boundary plane. This problem is of interest in construction, since it may be considered as the basis for the study of load distribution on the ground below the foundation of a building.

Formulation of the elasticity problem

A solid body limited by only one plane is subjected to a force P that is perpendicular to, and concentrated on, an infinitely small area of the plane. We make the assumption that the stress produced by the action of the load decreases to zero at great distances from the point of application. Clearly, the resulting stress and strain fields must be symmetrical about the axis provided by the line of application of the force.

This problem was first studied and solved by the Boussinesq method.[18] Here we present the solution in cylindrical coordinates:

We have avoided simplifications that could mislead the students.

$$\sigma_r = \frac{P}{2\pi}\left[\frac{(1-2v)}{r^2}\left(1-\frac{z}{R}\right)-\frac{3r^2z}{R^5}\right]$$

$$\sigma_z = -\frac{3P}{2\pi}\frac{z^3}{R^5}$$

$$\sigma_\theta = \frac{P(1-2v)}{2\pi}\left(\frac{-1}{r^2}+\frac{z}{r^2R}+\frac{z}{R^3}\right)$$

$$\tau_{rz} = -\frac{3P}{2\pi}\frac{rz^2}{R^5}\ ,$$

where v is the Poisson coefficient, r is the cylindrical radius,

z is the depth, R is the distance from the origin, σ_r is the radial component of the normal stress, σ_z is the vertical component of the normal stress, σ_θ is the angular component of the normal stress, and τ_{rz} is the shear stress in the r-z plane.

This solution satisfies, as it should, the conditions of internal equilibrium and consistency. Moreover, $\sigma_r = \tau_{rz} = 0$ at all points of the plane except for $r = z = 0$. At this point, the value of σ_z is infinite because a finite force is assumed to be acting upon an infinitely small area. In the infinite plane all tensile and shear stresses are negligible at sufficiently large distances from the point of application of the force. Finally, it may also be proved that the tensile stress that acts upon the surface of a cylinder of infinitely small radius and height surrounding the point of application of the external force provides an internal reaction force equal and opposite to P.
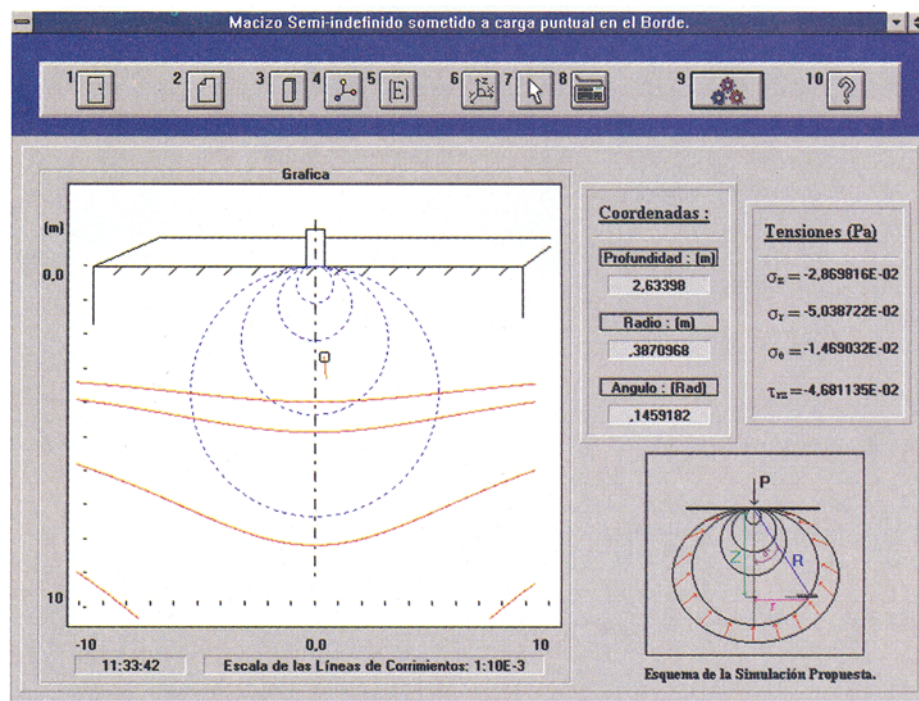

Figure 5. Simulation workplace for a problem in elasticity presents a schematic diagram (esquema) of the problem at the lower right and graph of the computed results (gráfica) at the left. The problem is that of a semi-infinite elastic body subjected to a force at one point on the surface. The buttons are explained in the text.

Visualization and animation

The simulation programs open with an initial animation to attract the student's interest. The student is able to select from among several other animations and digital images.

In the case of the theory-of-elasticity example, once the user chooses the simulation option, a screen appears providing six choices. This screen allows users to select from the six representative examples that were listed above.[18]

The images in Fig. 4 are two stills from one of the animations. Students can observe how a concrete block moves through the air and falls to the ground, creating an internal reaction.

A simulation workspace for the elasticity example appears in Fig. 5. This workspace presents users with a button bar, graphical display region, and space for entering numerical data. The 10 buttons, labeled by icons, give students these choices:

1. Return to main menu.
2. New simulation: Delete values entered previously and restore initial data.
3. Pressure: Enter a value for pressure at the contact point.
4. Poisson coefficient: Enter a value for the Poisson coefficient of earth.
5. Coefficient of elasticity: Enter a value for the elasticity coefficient of earth.
6. Change scale: Scale the workspace with the intervals desired.
7. Specify by mouse: Select, by mouse, the positions where stresses are to be calculated.
8. Specify by keyboard: Enter, by keyboard, the positions in different ways: radius and angle, depth and angle, or depth and radius.

9. Calculate: Check whether all necessary values have been entered and evaluate the stress.
10. Help.

Summary and more information

The INSIMU Project is structured according to the traditional teaching units of mechanics, electromagnetism, heat transfer, atomic physics, and the theory of elasticity. It is Windows-based and has a user-friendly interface. It includes a tutorial system to help teachers in the instruction and evaluation of students. Sample algorithms in Visual Basic to demonstrate the INSIMU software are available at ftp://www.aip.org/cip/cip_sourcecode.

From the Department Editor: Please send your comments, suggestions, and manuscripts for submission to this column to Dr. Denis Donnelly, Department of Physics, Siena College, Loudonville, NY 12211. E-mail: donnelly@siena.edu.
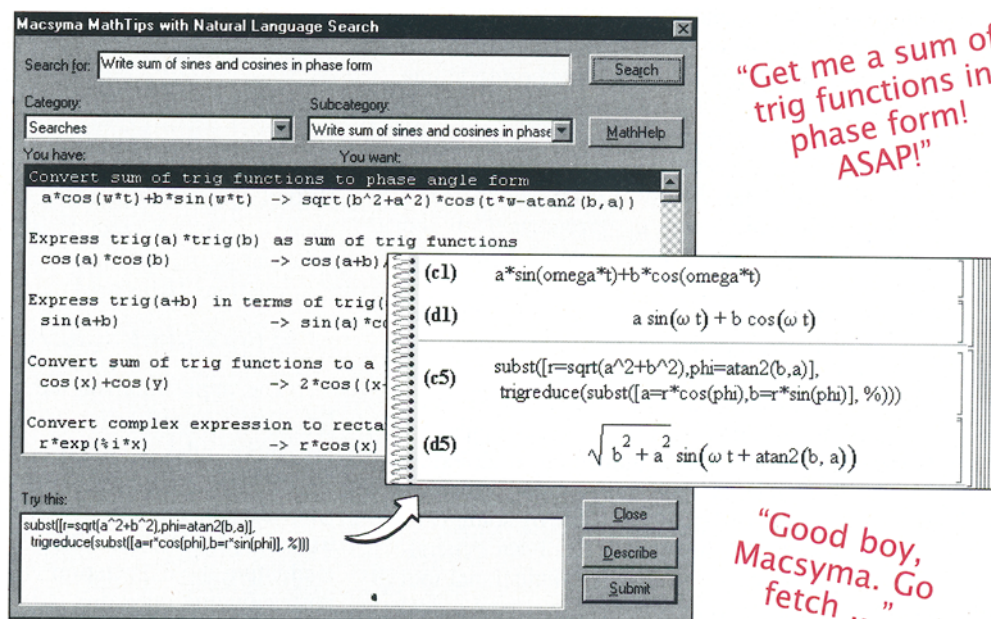
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